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A PHYSIOLOGICAL EVALUATION OF A PROTOTYPE AIR-VEST MICROCLIMATE COOLING SYSTEM

U S ARMY RESEARCH INSTITUTE OF ENVIRONMENTAL MEDICINE

Natick, Massachusetts

AUGUST 1991

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Human subjects participated in these studies after giving their informed consent. Investigators adhered to AR 70-25 and USAMRDC Regulation 70-25 on Use of Volunteers in Research.

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A PHYSIOLOGICAL EVALUATION OF A PROTOTYPE AIR-VEST MICROCLIMATE COOLING SYSTEM

by

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13. ABSTRACT *(Maximum 200 words)*

These experiments were conducted to answer three specific research questions about the effectiveness of a prototype air-cooled vest with design changes that make it useful for helicopter crews as well as armored vehicle crews. The results of these experiments show that: 1) Under matching cooling conditions, the NATICK prototype air-cooled vest (PAV) is as effective as the NATICK microclimate air-cooled vest (MAV) at reducing heat strain and increasing exercise performance time; 2) With the diffuse air-flow provided by the PAV, subjects experience no sensation of contact burning from air delivered at 45°C; 3) In a trade-off between flow rate and inlet temperature, subjects showed improved performance with air provided at 30Low compared to 40Hi even though 40Hi provided greater calculated cooling potential. It is concluded from these results that: 1) The PAV would provide a suitable replacement for the MAV; 2) The PAV could be used at higher ambient temperatures than the MAV; 3) If design changes in vehicle cooling equipment necessitates a trade-off between flow rate and cooling, they should favor providing lower temperatures over higher flow rates.

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TABLE OF CONTENTS

LIST OF FIGURES

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Technical support in operating the vests was provided by I.Y. Kim of the Individual Protection Directorate, U.S. Army Natick Research, Development and Engineering Center.

EXECUTIVE SUMMARY

A need for microclimate cooling has been established for aviators; and the currently fielded microclimate air-cooled vest (MAV), worn by tank crews in the M1A1 main battle tank, is not compatible with Army aviation equipment. The Natick Army Research Development and Engineering Center has developed a prototype microclimate air-cooled vest (PAV) which is designed for aviators and delivers a more diffuse air-flow over the torso than the MAV. This study compared the physiological responses of volunteers exercising in MOPP 4: 1) in both MAV and PAV in a simulated desert (45°C, 30% rh) environment with air provided to both vests at 30°C and 40°C and a 7.1 $L{\bullet}sec^{-1}$ flow rate; 2) in PAV in the desert environment with two conditioned air temperatures (30° and 40°C) and two flow rates (4.7 and 7.1 $L{\bullet}sec^{-1}$; and 3) in PAV with simulated desert and tropic (35°C, 70% rh) environments with ambient air provided to the vests at two flow rates (4.7 and 7.1 $L{\bullet}sec^{-1}$). These experiments showed 1) PAV was as effective as MAV in decreasing heat storage at the chosen cooling temperatures and flow rate in the desert environment; 2) conditioned air at 30°C (86°F, 30%rh) to PAV at 7.1 $L{\bullet}sec^{-1}$ prolonged the endurance time three fold for volunteers walking in the desert environment as compared to no cooling (90 min versus 31 min), while the 30°C air at 4.7 $L{\bullet}sec^{-1}$ more than doubled endurance time (72 min), and ambient air to PAV at both flows prolonged endurance time (approximately 50 min versus 35 min) in the tropic environment compared to no cooling; 3) there were no signs or symptoms of contact burning when air was provided to the PAV at ambient desert conditions. Air provided to the vest at 40°C in the desert environment did not improve performance even though calculated cooling at the high flow rate was greater than calculated cooling with 30° air provided at the low flow rate. It is concluded from these experiments that: 1) the PAV would provide a suitable replacement for the MAV; 2) the PAV could be used at higher ambient temperatures than the MAV; 3) any design changes in vehicle cooling equipment which would necessitate a trade-off between flow rates and temperature regulation should favor lower temperatures over higher flow rates.

INTRODUCTION

During military operations, combat vehicle crewmen and air crewmen encounter heat stress from a combination of environmental (e.g., ambient temperature, humidity and radiant heat load) and mission related (e.g., metabolic rate or clothing ensemble) factors. During nuclear/biological/chemical (NBC) operations, the requirement for wearing highly insulative clothing with low permeability to water vapor, severely limits dry and evaporative heat exchange between the soldier and the environment. As a result, the use of NBC protective clothing potentiates the possibility of marked heat strain in soldiers. Heat stress associated with performing exercise wearing NBC protective clothing is well documented (6,8,18,20). Without some form of microclimate cooling under the protective clothing, soldiers are often limited to short work periods (6,8,14).

Macroclimate cooling, i.e., air conditioning the entire crew compartment, is not a feasible approach to alleviating the heat stress problem in combat vehicles for a number of reasons: 1) Macroclimate cooling increases the power requirements for the vehicle; 2) The size and weight of the cooling equipment are excessive; 3) Macroclimate cooling has been shown ineffective in satisfactorily reducing the thermal strain of crewmen wearing NBC protective clothing (20); and 4) Crewmen in NBC protective clothing are called on to perform dismounted operations, such as vehicle repair, maintenance and resupply. A microclimate cooling vest system may be disconnected from the vehicle cooling source and reconnected to an external cooling source. Therefore, cooling system development has focused on microclimate cooling, that is, cooling the environment immediately next to the body and under the protective clothing. Microclimate cooling is accomplished by employing either air or liquid as the medium to transfer body heat. While the most effective microclimate cooling system would cover the entire body (17,21), practical constraints on system design allow selected cooling of limited body areas. Cooling the torso removes sufficient heat to alleviate heat strain and extend soldier performance time (3,11-18,20-22).

The Individual Protection Directorate (IPD), U.S. Army Natick Research, Development and Engineering Center (NATICK) has a systematic program to develop microclimate cooling systems. IPD has developed an air-cooled system which delivers air to a torso vest and protective mask. This system was successfully tested both in the laboratory (4,11,14,16) and in the field (4). Tests were conducted in environmental chambers, during which volunteers exercised in hot environments at several different exercise intensities, and received air flow to the cooling system at varied flow rates, temperatures and relative humidities (4,11,14,16).

These tests were compared to control experiments with no vest cooling or to the US ARIEM computer generated model for heat strain under similar environmental conditions and clothing. The cooling system decreased heat storage rate and increased performance time. The system had one potential problem, in that ambient air at 49°C blown through the vest produced contact burning (16). Field tests were run on crews in the M1A1 tank fighting a mock 12-hour battle, both in the desert of Yuma, Arizona and the jungle of the Republic of Panama (3). No significant body heat storage occurred during either battle scenario for crew members receiving conditioned air through the NATICK system. The results of these tests were that the microclimate cooling system was fielded and is now part of the standard equipment on the M1A1 main battle tank.

The success of this air-cooled system for armored personnel resulted in the aviation community requesting a similar system. The presence of high ambient temperatures inside a variety of helicopters has been documented (1,9,19). The potential exists for helicopters to be in areas of chemical contamination, therefore flight crews must be prepared to wear mission oriented protective posture (MOPP) clothing. These crewmen face a problem similar to tank crews and microclimate cooling should be beneficial. However, the current air-cooled vest as fielded in the M1A1 tanks is too bulky and the hoses and hard manifolds do not interface with the equipment used by aviators. Therefore, IPD re-designed the air-cooled vest and has developed a prototype which conforms with aviation equipment. IPD also changed the air-flow configuration, producing a more diffuse air-flow to reduce the possibility of contact burns at high ambient temperatures.

The purposes of this study were: 1) to determine if the PAV is as effective as the MAV for providing body cooling; 2) to determine the trade-offs in cooling effectiveness when altering inlet temperatures and air flow rates; and 3) to determine if the more diffuse air-flow to the torso delivered by the PAV will reduce the potential for contact burning when very hot inlet air is provided. In order to address these questions the following experiments were conducted: 1) to compare physiological responses during exercise in a hot-dry environment between the MAV and the PAV: 2) to evaluate the PAV at several ambient temperatures and flow rates and compare results to control experiments with no cooling; 3) to evaluate the PAV with air flow to the vest at high ambient temperatures to evaluate the potential for contact burning.

METHODS

SUBJECTS

Six male soldiers volunteered to participate after being informed of the purpose and procedures of the study, any known risks and their right to terminate participation at will without penalty. Each expressed understanding by signing a statement of informed consent. Their height, weight, and estimate of per cent body fat by skinfold thickness at four sites (5) were determined. The subjects' mean (±S.D.) age was 24 (±9) years, height was 180 (±9) cm, weight was 78.5 (±15.9) kg, body surface area (A_D) was 1.97 (±0.23) m^2 and body fat was 16.8 (±6.5)%.

COOLING SYSTEMS

The NATICK air-cooled microclimate vest (MAV; Figure 1), which is currently fielded in the M1A1 tank, provides chest, neck and back cooling via a hose and manifold system mounted on an open weave fabric. The hoses are lightweight, crush resistant and maintain a constant diameter when bent. Supplied air is distributed by the vest's connector and delivered in ratios of approximately 40% to the chest, 40% to the back and 20% to the neck. The air arrives via a chest manifold which directionally distributes the air through four holes for chest cooling. The remaining air flow continues through two hoses which have holes for neck cooling, and terminate at a hard circular manifold where the remaining air is spread across the back through 10 holes located on the periphery of the manifold. The vest provides a 2.54 cm space between the body and the next layer of clothing for cooling to take place. The vest is lightweight at 0.45 kg and offers low resistance to airflow. The vest is worn over an undershirt and beneath the crewman's fragmentation protective vest.

The IPD prototype air-cooled microclimate system (PAV; Figure 2) required design changes to conform with the helicopter crews' equipment. The lap harness worn while flying necessitated moving the umbilical from the front to the side of the vest. The design of the aviator's helmet and placement of shoulder harnesses necessitated removal of the neck hoses, which account for 20% of the air dispersal in the MAV. Additionally, the hard, plastic manifold in the back of the MAV has been removed. The result is a flexible 0.68 kg vest which wraps around the user's torso and is held in place with a velcro closure and shoulder straps. Unlike the limited, directional air flow from the few openings in the MAV, the prototype vest delivers a diffuse air flow around the torso from many small holes covering the

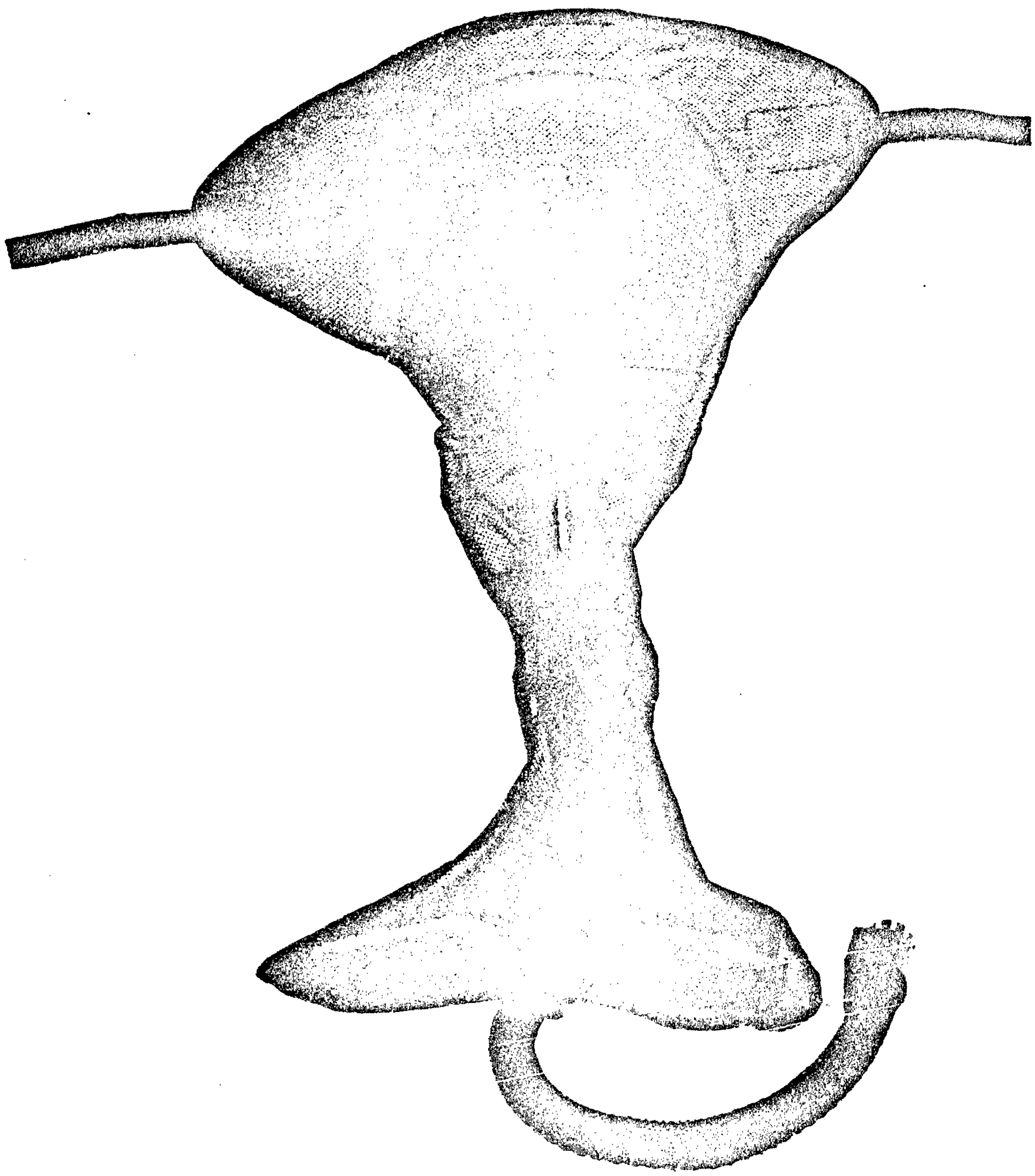

Figure 1: The NATICK microclimate air-cooled vest (MAV) currently fielded in the M1A1 armored vehicle.

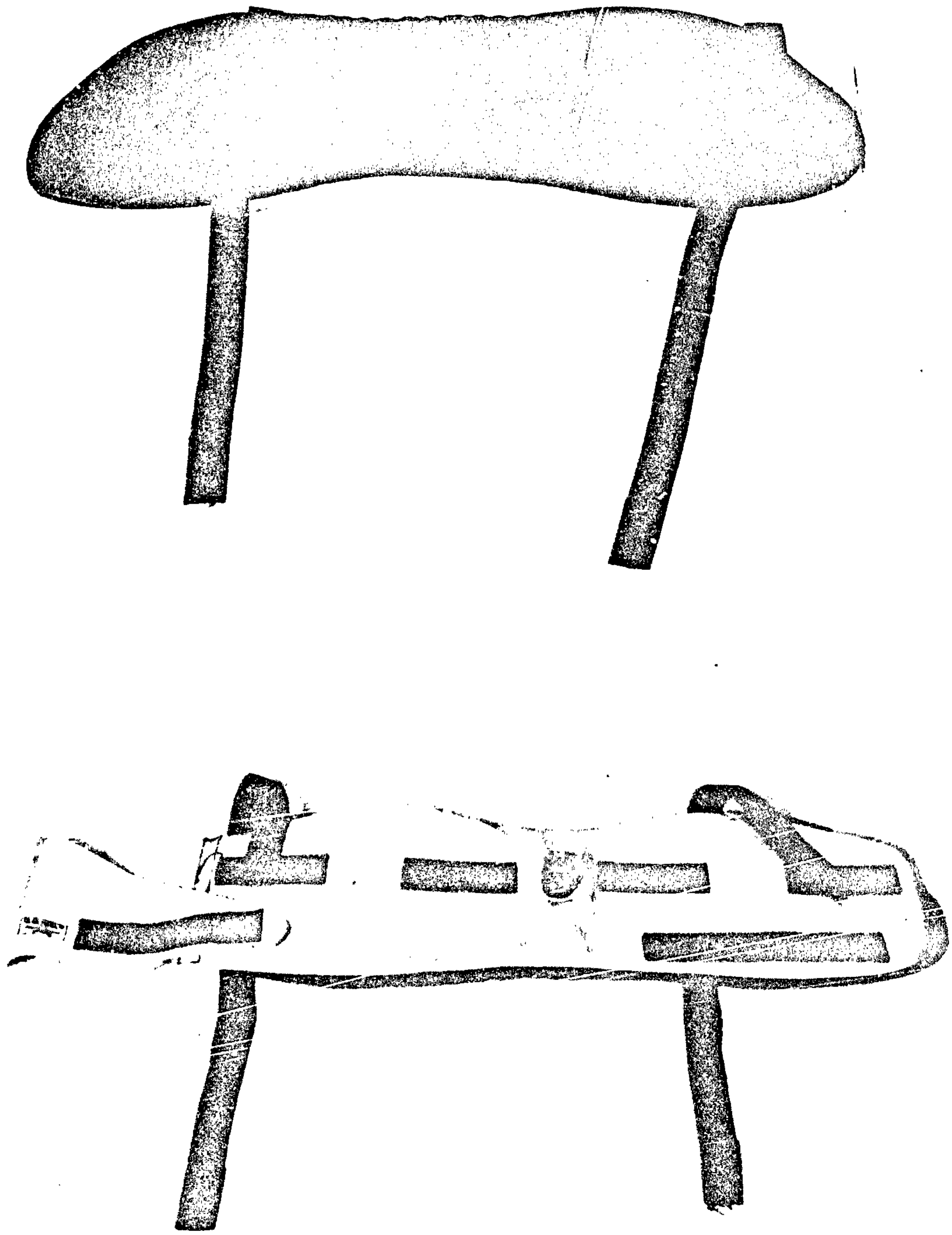

Figure 2: The NATICK prototype air-cooled vest (PAV) designed to be compatible with helicopter crew uniforms.

entire inside surface of the vest. A 0.64 cm spacer between the vest surface and user's body allows the air to flow around the torso. This vest also is worn directly over an undershirt.

STUDY DESIGN

The study was conducted in Natick, Massachusetts during August. Although the subjects were partially heat acclimatized, they participated in a seven day heat acclimation program prior to experimental testing. Heat acclimation was confirmed by non-significant changes in heart rate and core temperature between three consecutive days. Each day during the heat acclimation program, the subjects attempted a 120 min walk (1.56 $m \cdot sec^{-1}$ at a 4% grade) on a treadmill in a 45°C T_{db}, 23.3°C T_{dp} (30% rh), 1.0 $m \cdot sec^{-1}$ wind speed, environment. During acclimation, subjects dressed in shorts, socks and athletic shoes. On one afternoon following a morning heat acclimation, the subjects returned to the environmental chamber for a familiarization session. For this session, the dry bulb in the chamber was reduced to approximately 20°C to minimize heat stress for the subjects. During this session the subjects dressed as per experimental heat stress tests (see below). At approximately 10 minutes into the familiarization session, subjects removed their protective masks and hoods to enable measurement of metabolic rate via open circuit spirometry. Two minute samples of expired air were collected in Douglas bags during steady state exercise. Each sample was analyzed, for oxygen content (Applied Electrochemistry S-3A oxygen analyzer), for carbon dioxide content (Beckman LB-2 carbon dioxide analyzer) and for pulmonary ventilation (Tissot respirometer). The treadmill grade was then raised and when subjects again reached steady state a second set of expired air samples were collected and analyzed. Results from the metabolic rate calculations were used to determine the treadmill speed and grade used during experimental testing.

Following the heat acclimation program, each subject attempted 12 Heat Stress Tests (HST) each consisting of 180 minute walks at a metabolic rate of approximately 425 watts (treadmill at 1.34 $m \cdot sec^{-1}$, 0% grade). In all HSTs, subjects wore a t-shirt, cooling vest, combat vehicle crewman (CVC) fragmentation protective vest, CVC Nomex coveralls, chemical/biological (CB) overgarment (pants and jacket), M-17 protective mask, butyl rubber hood, CB butyl rubber gloves with cotton liners and CB butyl rubber overboots. Helmets were not worn. The protective masks' filter elements were removed to normalize breathing by reducing resistance and decreasing possible irritation from ammonia fumes found in some old filters. The estimated insulative value (clo) of the uniform was 2.75, while the estimated measure of vapor permeability (I_m) was 0.30 (Levell, unpublished data).

Nine of the HST were performed at 45°C T_{db}, 23.3°C T_{dp} (30% rh), 1.0 m•sec^{-1} wind speed, to simulate desert conditions. Table 1 lists vest type, air flow, air inlet temperature and theoretical maximal cooling rate during each HST in the desert conditions. Maximal cooling rates were calculated as the total evaporative and convective cooling potentials under the given ambient temperature, inlet temperature and flow rate combinations. The flow rate and temperature combinations were provided in a counterbalanced order of presentation to eliminate order bias. Within the framework of Table 1, the experimental questions were answered by: 1) Comparing the physiological responses between HSTs 1 and 3 and those between HSTs 2 and 4 to compare the PAV directly against the MAV under identical conditions; 2) Comparing the physiological responses among HSTs 3-9 to compare different flow rate and temperature combinations with a Control experiment; 3) Evaluating HSTs 5 and 8 to determine whether contact burning occurred from hot-dry air provided to PAV at two flow rates. The PAV was worn in all Control tests with no cooling.

Table 1. Microclimate cooling system configurations and theoretical cooling provided for the heat stress tests (HST) in the 45°C, 30% rh environment.

HST	VEST (type)	FLOW (L•sec^{-1})	VEST db (°C)	VEST dp (°C)	MAX COOLING (watts)
1	MAV	7.08	30.0	9.9	680
2	MAV	7.08	40.0	18.8	554
3	PAV	7.08	30.0	9.9	680
4	PAV	7.08	40.0	18.8	554
5	PAV	7.08	45.0	23.3	273
6	PAV	4.72	30.0	9.9	454
7	PAV	4.72	40.0	18.8	369
8	PAV	4.72	45.0	23.3	182
9	CONTROL	0	-	-	0

7.08 L•sec^{-1} = Hi flow
4.72 L•sec^{-1} = Low flow

In addition, three HSTs were performed with PAV at 35°C T_{db}, 28.6°C T_{dp} (70% rh), 1.0 m•sec^{-1} wind speed, to simulate tropic conditions. Table 2 lists the cooling vests, air flow, air inlet temperature and theoretical maximal cooling rate in each HST in the tropic condition. In two of these HSTs, each man received an ambient air flow from the PAV, and the third test served as a Control with no cooling. The different flow rate and inlet temperature combinations were again provided to the subjects in a counterbalanced order to help eliminate order bias. The three experiments evaluated the effect of flow rate (HST 1 versus 2) and the effect of microclimate cooling (HSTs 1 and 2 versus 3).

Throughout the remainder of this report, the two flow rates are designated as Hi for 7.08 L•sec^{-1} and Low for 4.72 L•sec^{-1}. To identify each cooling configuration, the flow rate is combined with the dry bulb temperature of air supplied to the vest, such as 30Hi or 30Low.

Table 2. Microclimate cooling system configurations and theoretical cooling provided for the HST in the 35°C, 70% rh environment.

HST	VEST (type)	FLOW (L•sec^{-1})	VEST db (°C)	VEST dp (°C)	MAX COOLING (watts)
1	PAV	7.08	35.0	28.6	363
2	PAV	4.72	35.0	28.6	242
3	CONTROL	0	-	-	0

7.08 L•sec^{-1} = Hi flow
4.72 L•sec^{-1} = Low flow

PROCEDURES

During all heat exposures, both heat acclimation and HST, the subjects inserted a rectal thermistor approximately 10 cm beyond the anal sphincter for the measurement of core temperature (T_{re}). Additionally, in all heat exposures, heart rate (HR) was measured from an electrocardiogram (electrodes CM5 placement) which was telemetered to an oscilloscope cardiotachometer unit. On the HST days, all subjects were fitted with a four site (head, arm, chest, leg) thermocouple harness for the measurement of skin temperatures. Mean weighted skin temperature ($\bar{T}_{sk}$) was calculated from the arm, chest and leg measurements to evaluate the effectiveness of the various cooling configurations (2). Head temperature (T_{head}) under the impermeable butyl rubber hood was measured separately to examine if the cooling vest had any effect on head skin surface temperature. T_{re} and $\bar{T}_{sk}$ were recorded every minute, while HR was monitored continuously and recorded every 5 minutes. During the HST, subjects were allowed to drink water ad libitum through a plastic drinking straw inserted under the protective mask. All water intake was measured. Whole body sweating rate (M_{sw}) was calculated from changes in pre to post experiment nude body weights, and evaporative heat loss (E_{tot}) was estimated by changes in pre to post experiment dressed weights which included the weight of nonevaporated sweat trapped in the uniform. Heat storage (S) in $W{\cdot}m^{-2}$ was calculated from the equation $S=[(m_b{\cdot}c_b)/A_D]{\cdot}(d\bar{T}_b/dt)$, where m_b is the mean body weight (kg) during the HST, c_b is the specific heat constant 0.965 ($W{\cdot}h{\cdot}{}^{\circ}C^{-1}{\cdot}kg^{-1}$), A_D is the DuBois surface area (m^2), $d\bar{T}_b$ is the change in mean body temperature (°C) where $\bar{T}_b=0.11{\cdot}T_{sk}+0.89{\cdot}T_{re}$, and dt is the exposure time (h) of the HST. During all experiments, testing was terminated if T_{re} reached 39.5°C, HR remained at or exceeded 180 $b{\cdot}min^{-1}$ for five consecutive minutes, subjects requested removal or the medical monitor determined a subject should discontinue exercise for his safety. During experiments with air to the vests at 45°C, the volunteers were asked to provide a subjective sensation of contact burning or skin irritation. The volunteers' torsos were visually inspected after the 45°C experiments for any sign of redness or irritation. HST were separated by 24 hours to allow adequate recovery.

STATISTICAL ANALYSIS

Analyses of variance with repeated measures were used to compare variables of T_{re}, $\bar{T}_{sk}$, S, T_{head}, HR, M_{sw}, E_{tot} and endurance time (ET) among the HST. Analyses of T_{re}, $\bar{T}_{sk}$, S, T_{head} and HR were performed on data recorded at 28 minutes for the tests conducted in the 45°C environment (the final time with data on all subjects in all cooling configurations) and at 36 minutes for tests conducted in the 35°C environment (the final time with data on all subjects at both flow rates), so that analyses would include all subjects under all conditions. Analyses of S were also performed on data at 19 minutes in the 45° environment (the final time with data on all subjects in the Control experiment) and 23 minutes in the 35° environment (the final time with data on all subjects in the Control experiment) to compare rate of heat storage between Control and all cooling configurations. Tukey's test of critical differences was used when significant main effects were found in analyses of variance. All differences are tested at the $p<0.05$ level, unless otherwise noted. Data are reported as the mean (± standard deviation).

RESULTS

MAV vs PAV

The subjects' mean (±SD) metabolic rate was 436 (±68) watts during all exercise tests. Table 3 presents the endurance time (ET) and physiological responses during the simulated desert experiments. During these experiments, no significant differences were found between the MAV and PAV systems for any of the measured parameters.

Table 3. Mean (±SD) endurance time (ET) and physiological responses measured after 28 min of HST at 45°C, 30% rh wearing the NATICK air-vest (MAV) and the prototype air-vest (PAV); cooling was provided at 30Hi and 40Hi.

HST	ET (min)	$\bar{T}_{sk}$ (°C)	T_{head} (°C)	T_{re} (°C)	HR ($b \cdot min^{-1}$)	M_{sw} ($g \cdot min^{-1}$)	E_{tot} ($W \cdot m^{-2}$)
MAV 30Hi	86 (33)	35.1 (1.1)	40.1 (2.3)	37.5 (0.3)	116 (10)	28.1 (4.6)	260 (78)
PAV 30Hi	90 (20)	34.6 (0.5)	39.5 (1.5)	37.4 (0.3)	117 (9)	27.2 (6.6)	238 (56)
MAV 40Hi	51 (15)	35.9 (0.9)	40.4 (1.6)	37.5 (0.2)	126 (13)	32.3 (4.9)	206 (59)
PAV 40Hi	56 (9)	35.4 (0.3)	40.8 (2.2)	37.5 (0.4)	122 (16)	31.3 (6.9)	228 (39)

PAV - 45°C T_{db}, 23.3°C T_{dp}

Figure 3 shows the mean endurance times for all cooling configurations. Endurance time in the 30Hi HST (90±20 min) was longer ($p<0.01$) than Control (31±12 min) and all other cooling configurations except the 30Low HST (72±10 min). Endurance time with 30Low was longer ($p<0.01$) than 45Low (41±9 min) and Control.

Core temperature analyzed at 28 minutes was not different among any of the cooling combinations (Table 4). The $\bar{T}_{sk}$ at 28 minutes (Table 4) was lower ($p<0.01$) for the 30Hi (34.6±0.5°C) than for the 45Hi (35.9±0.5°C) and 45Low (35.9±0.3°C) HST. T_{head} at 28 minutes was not different among any of the cooling configurations. The group means for T_{head} ranged from 39.5 to 41.0°C (Table 4). The heat storage at 19 minutes (the final time with data on all subjects during the Control HST (Figure 4)) was greater ($p<0.05$) during the Control HST (69 $W \cdot m^{-2}$) than in all cooling configurations except the 45Hi HST (55 $W \cdot m^{-2}$). There was no difference in S among any of the cooling configurations at 19 minutes, nor when S was analyzed at 28 minutes (Figure 5). HR (Table 4) was lower ($p<0.01$) at the 30Hi HST (117±9 $b \cdot min^{-1}$) than the 45Low HST (137±15 $b \cdot min^{-1}$). M_{sw} (Figure 6) was lower ($p<0.01$) in the 30Hi experiment (27±7 $g \cdot min^{-1}$) than in the 45Low experiment (35±5 $g \cdot min^{-1}$). M_{sw} in the Control experiment (44±10 $g \cdot min^{-1}$) was significantly greater than in all other experiments. Analyses of E_{tot} (Figure 7) indicated no differences among any of the cooling configurations or the Control HST, with values ranging from 182 to 260 $W \cdot m^{-2}$.

No symptoms of contact burning were reported by the subjects during the experiments with 45°C air provided to the vests; nor were any signs of irritation visible on their torsos at the end of the experiments.

Table 4. Physiological variables (mean ±SD) measured after 28 min of 45°C, 30% rh HST with different cooling combinations while wearing the PAV.

HST	$\bar{T}_{sk}$ (°C)	T_{head} (°C)	T_{re} (°C)	HR ($b \cdot min^{-1}$)
PAV 30Low	35.1 (0.6)	40.0 (2.3)	37.5 (0.4)	122 (11)
PAV 30Hi	34.6* (0.5)	39.5 (1.5)	37.4 (0.3)	117+ (9)
PAV 40Low	35.4 (0.4)	41.0 (1.8)	37.5 (0.2)	130 (14)
PAV 40Hi	35.4 (0.3)	40.8 (2.2)	37.5 (0.4)	122 (16)
PAV 45Low	35.9 (0.3)	40.4 (1.6)	37.6 (0.3)	137 (14)
PAV 45Hi	35.9 (0.5)	39.6 (3.1)	37.6 (0.2)	133 (14)

* less than 45Low, 45Hi ($p<0.05$)
\+ less than 45Low ($p<0.05$)

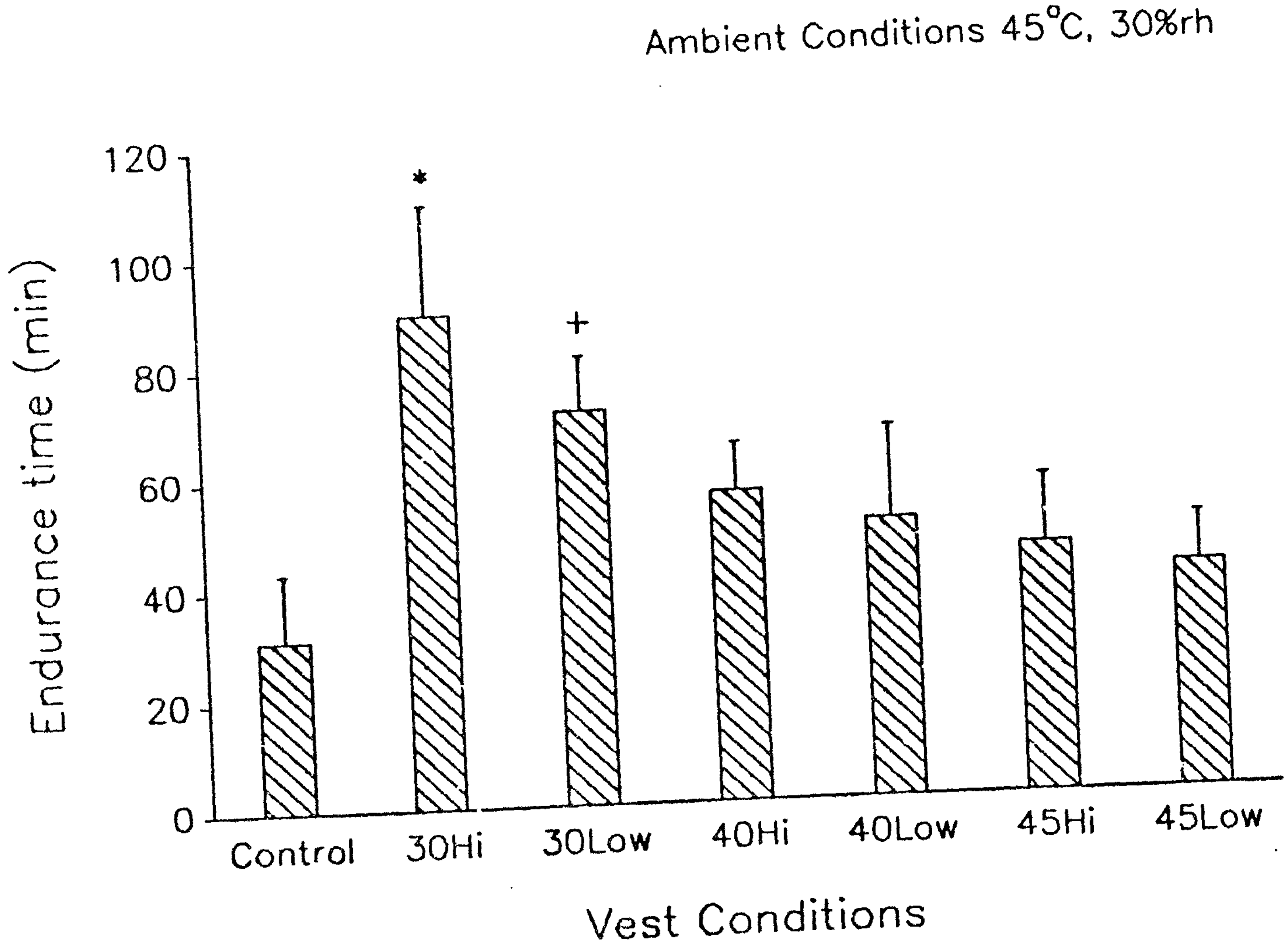

Figure 3 Mean ±SD endurance times wearing the PAV with no cooling (Control) and all temperature, flow rate combinations. * greater than Control, 40Hi, 40Low, 45Hi, 45Low. + greater than Control, 45Low.

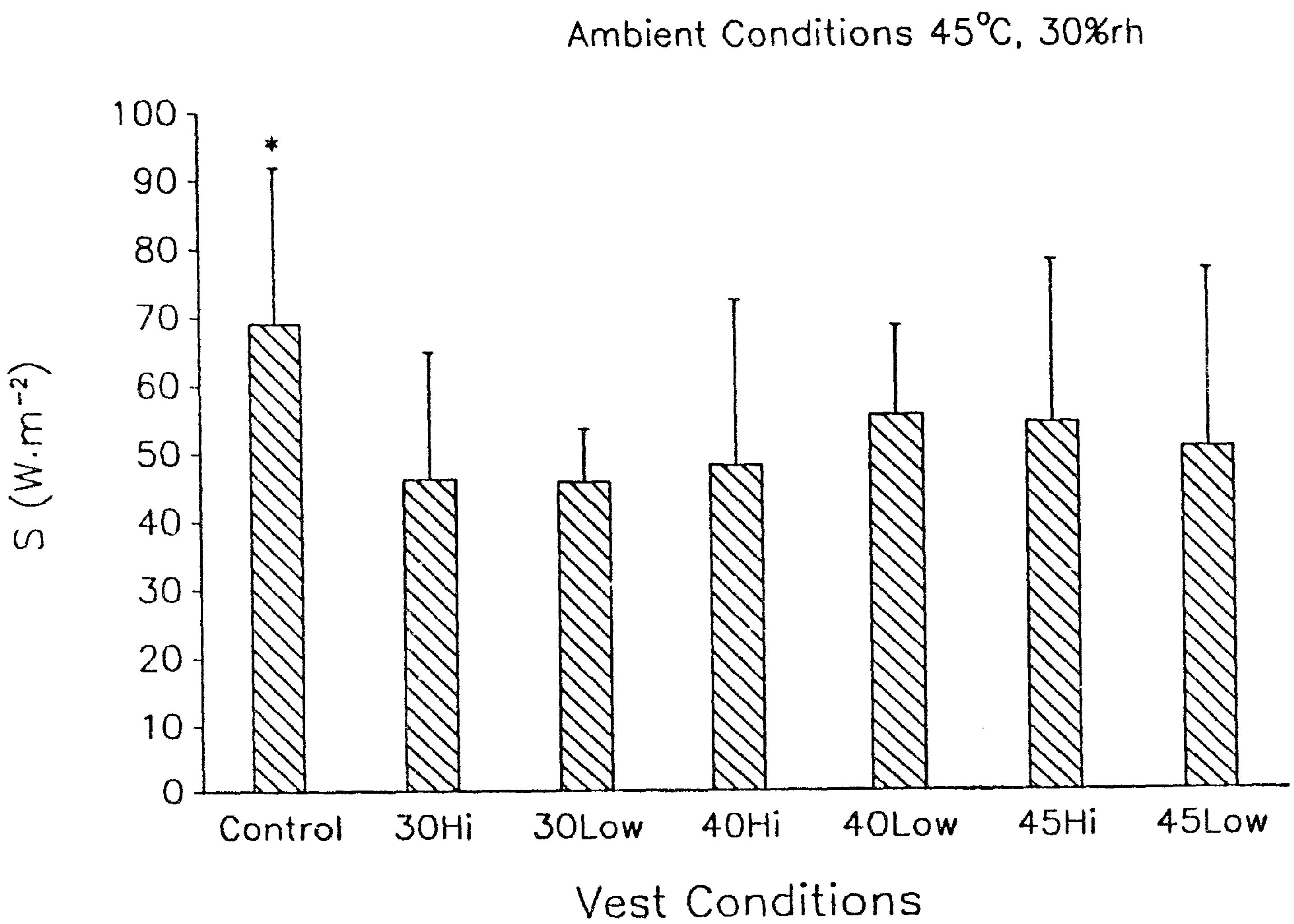

Figure 4 Mean ±SD 19 min heat storage (S) wearing PAV, with no cooling (Control) and all temperature, flow rate combinations.
* greater than 30Hi, 30Low, 40Hi, 40Low, 45Low.

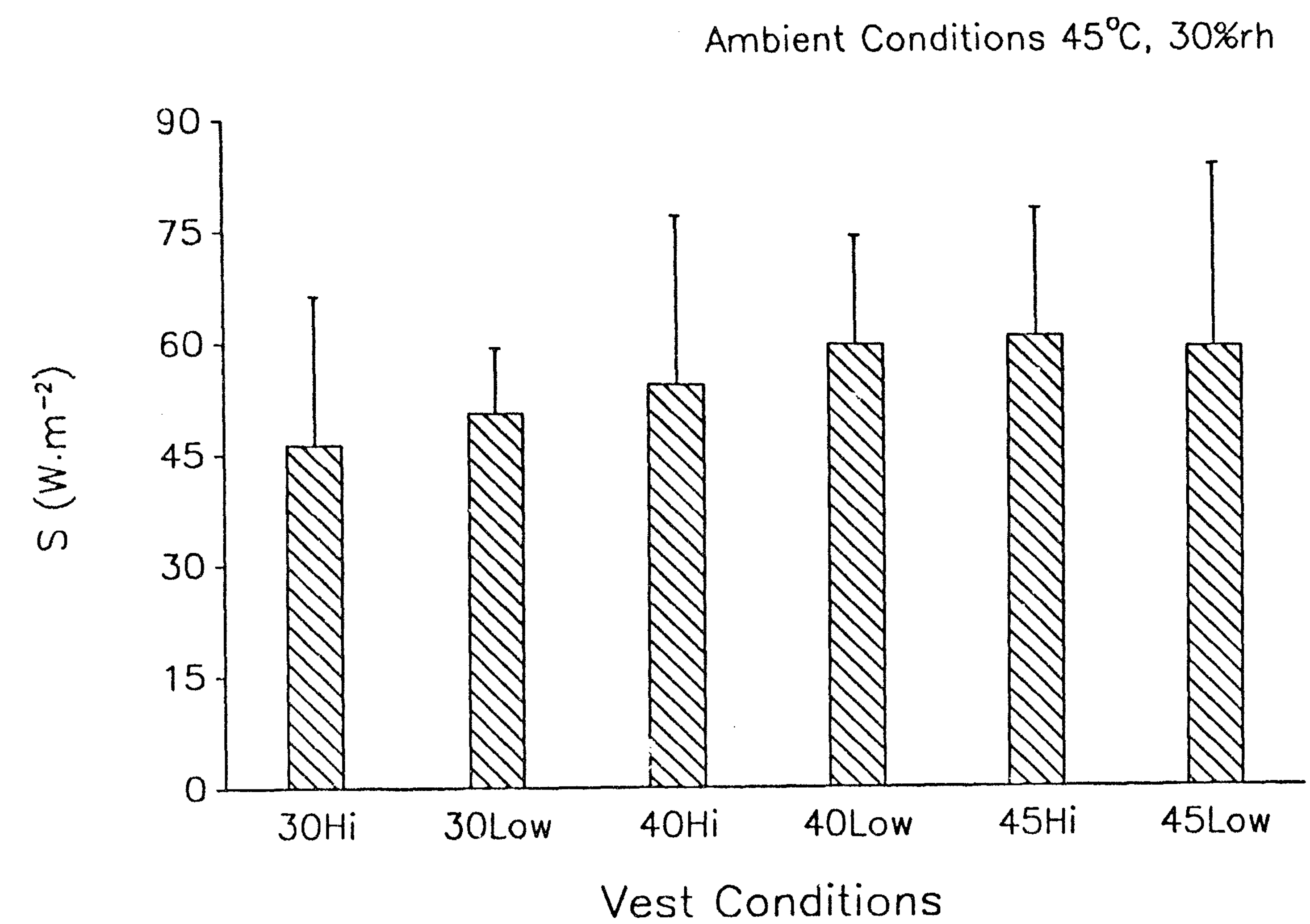

Figure 5 Mean ±SD 28 min heat storage (S) wearing PAV with all temperature, flow rate combinations.

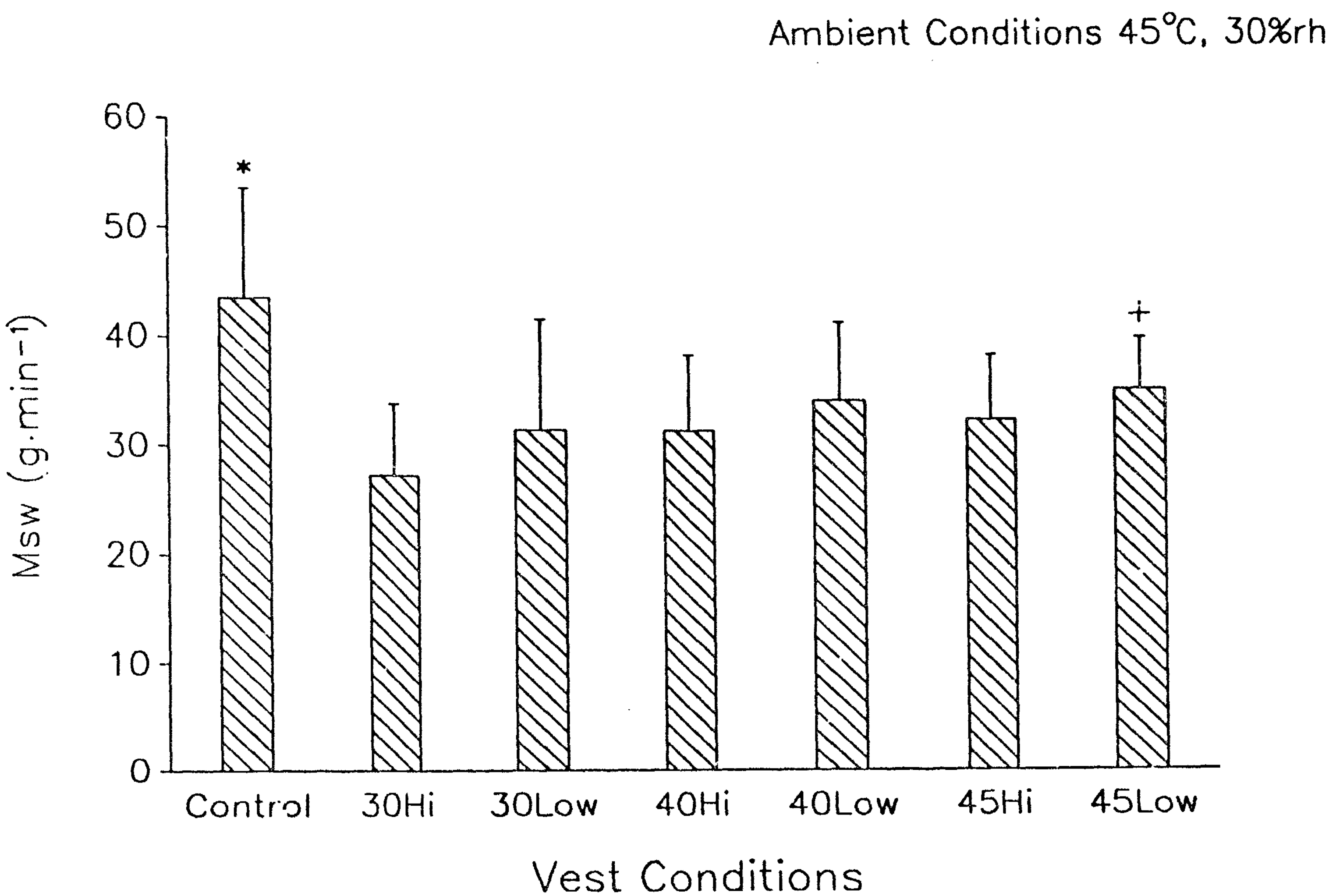

Figure 6 Mean ±SD sweating rates (M_{sw}) wearing the PAV with no cooling (Control) and all temperature, flow rate combinations.
* greater than all. + greater than 30Hi.

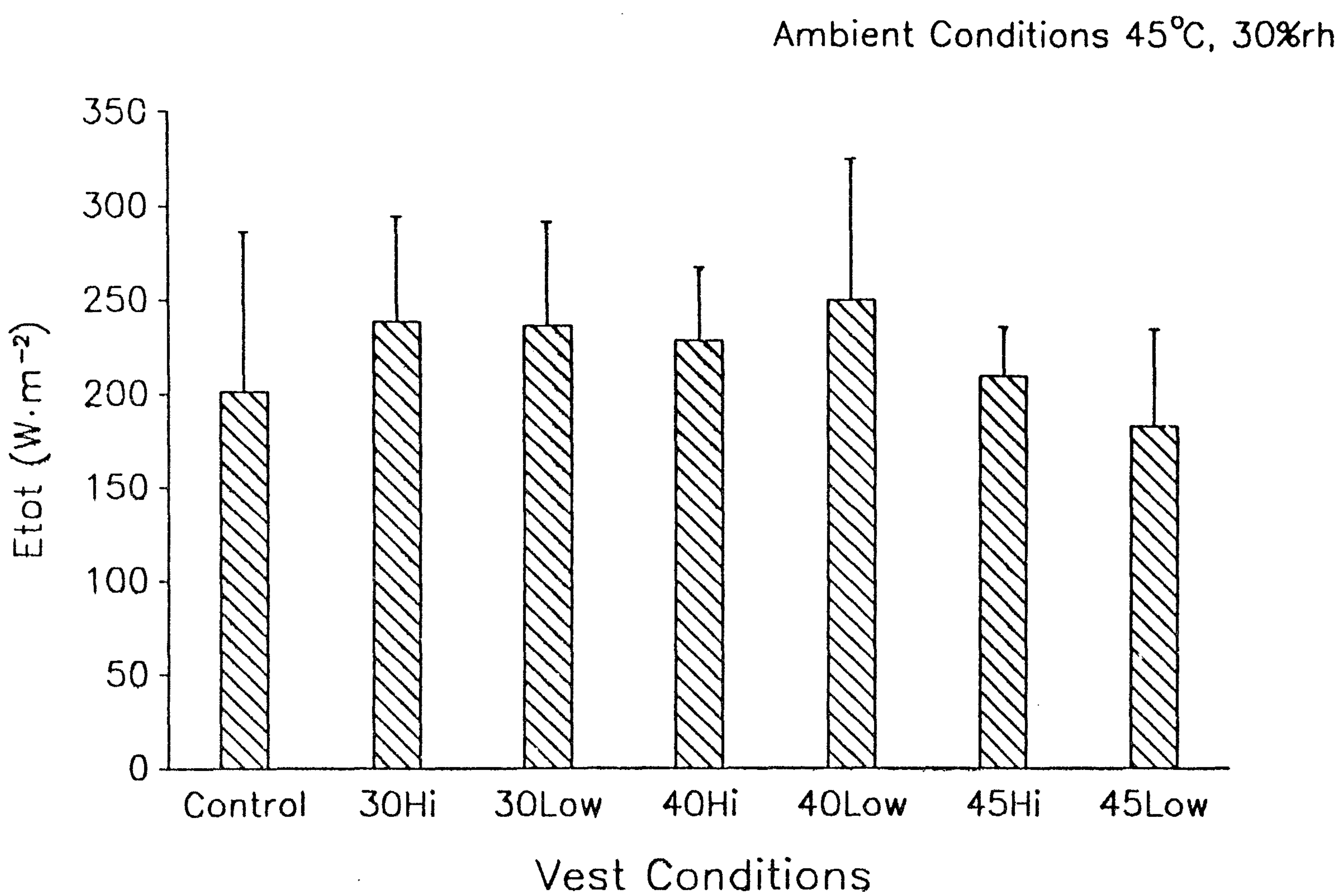

Figure 7 Mean ±SD evaporative cooling (E_{tot}) wearing the PAV with no cooling (Control) and all temperature, flow rate combinations.

PAV - 35°C T_{db}, 28.6° T_{dp}

Endurance time was less ($p<0.01$) during the Control experiment (35±10 min) than in either the 35Low (49±10 min) or 35Hi (50±11 min) HST (Figure 8). There were no differences in core temperature at 36 minutes (the final time with complete data on both cooling configurations) between 35Hi (37.6±0.2°C) and 35Low (37.4±0.2°C) (Table 5). $\bar{T}_{sk}$ and T_{head} were not different between the Hi and Low flow rate tests. The heat storage at 23 minutes (the last time with data on all subjects in the Control HST; Figure 9) was greater ($p<0.05$) for the Control HST (66 $W{\bullet}m^{-2}$) than either the 35Hi (38 $W{\bullet}m^{-2}$) or 35Low (46 $W{\bullet}m^{-2}$) HSTs. At 36 minutes, there was no difference in S between cooling provided with the two flow rates (Figure 10). There was no difference in HR between cooling with the Hi and Low flow rates. There were no differences in M_{sw} (Figure 11) or E_{tot} (Figure 12) among experiments with either of the flow rates or the Control HST.

Table 5. Physiological variables (mean ±SD) measured after 36 min of 35°C, 70% rh HST with ambient air at two flow rates in the PAV.

HST	$\bar{T}_{sk}$ (°C)	T_{head} (°C)	T_{re} (°C)	HR ($b{\bullet}min^{-1}$)
PAV 35LOW	36.0 (0.2)	36.7 (1.0)	37.6 (0.2)	122 (10)
PAV 35HI	35.9 (0.3)	37.2 (0.5)	37.4 (0.2)	122 (16)

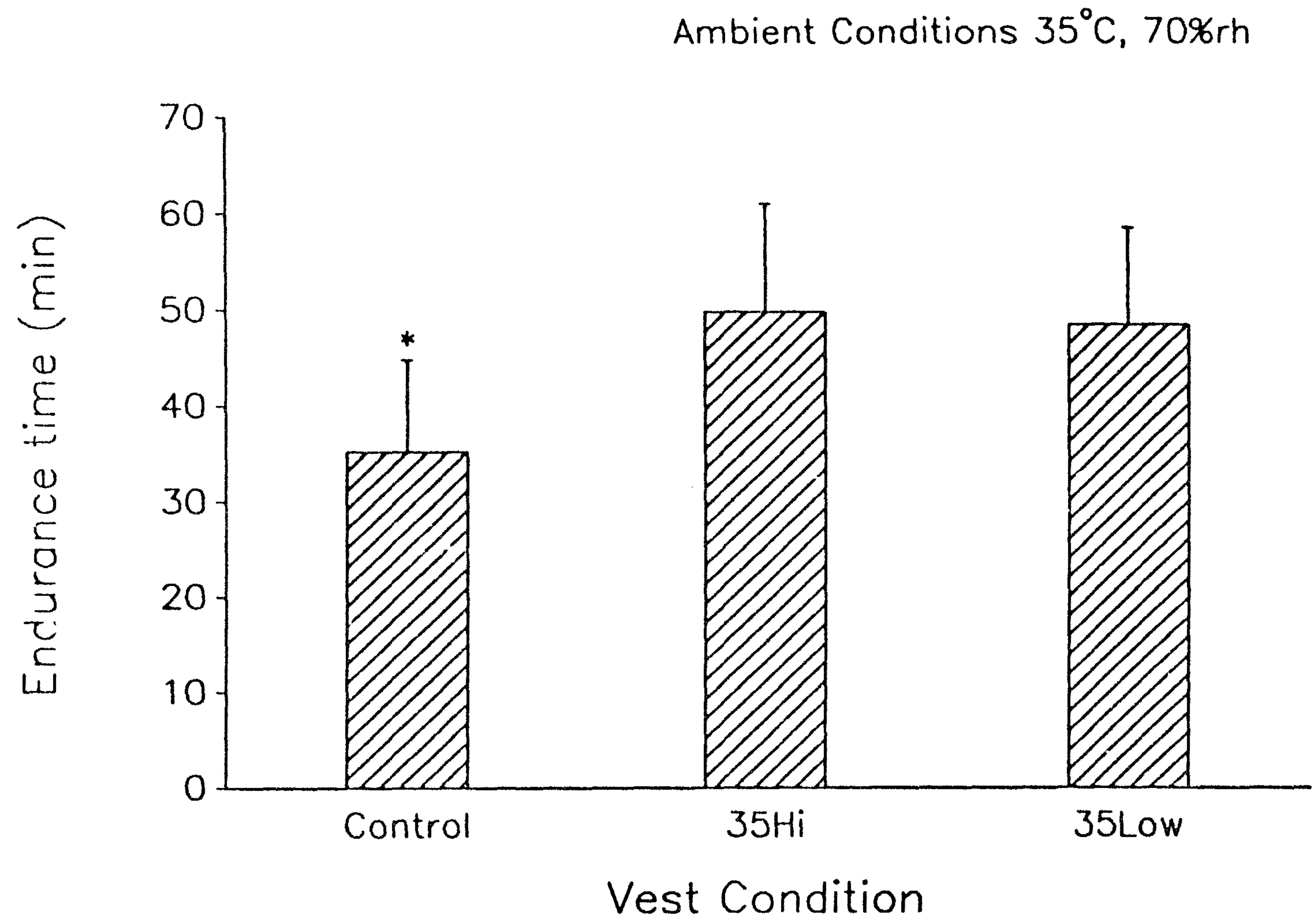

Figure 8 Mean ±SD endurance times wearing the PAV with no cooling (Control) and two flow rates of ambient air. * less than 35Hi and 35Low.

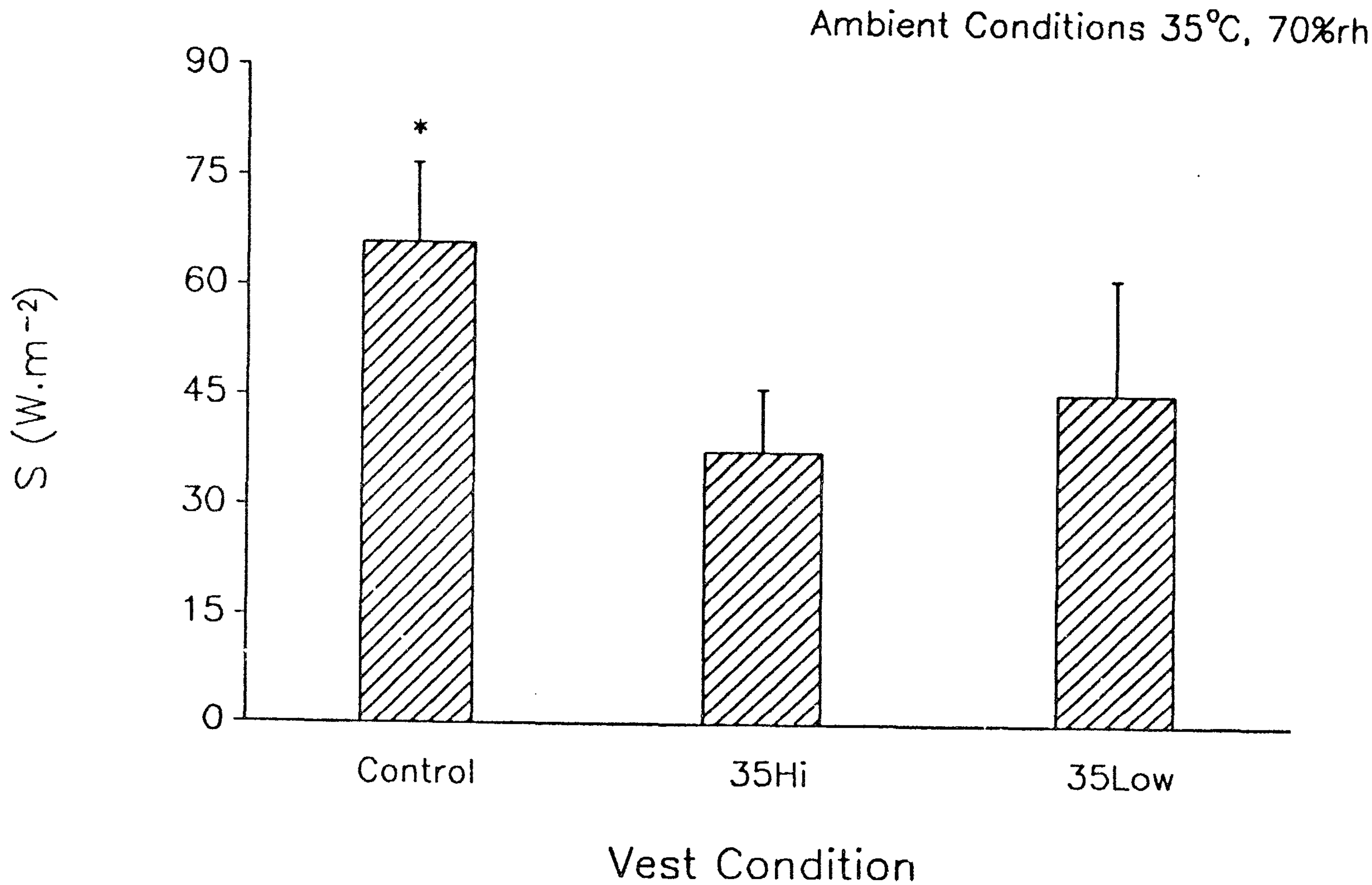

Figure 9 Mean ±SD 23 min heat storage (S) wearing PAV with no cooling (Control) and two flow rates of ambient air. * greater than 35Hi, 35Low.

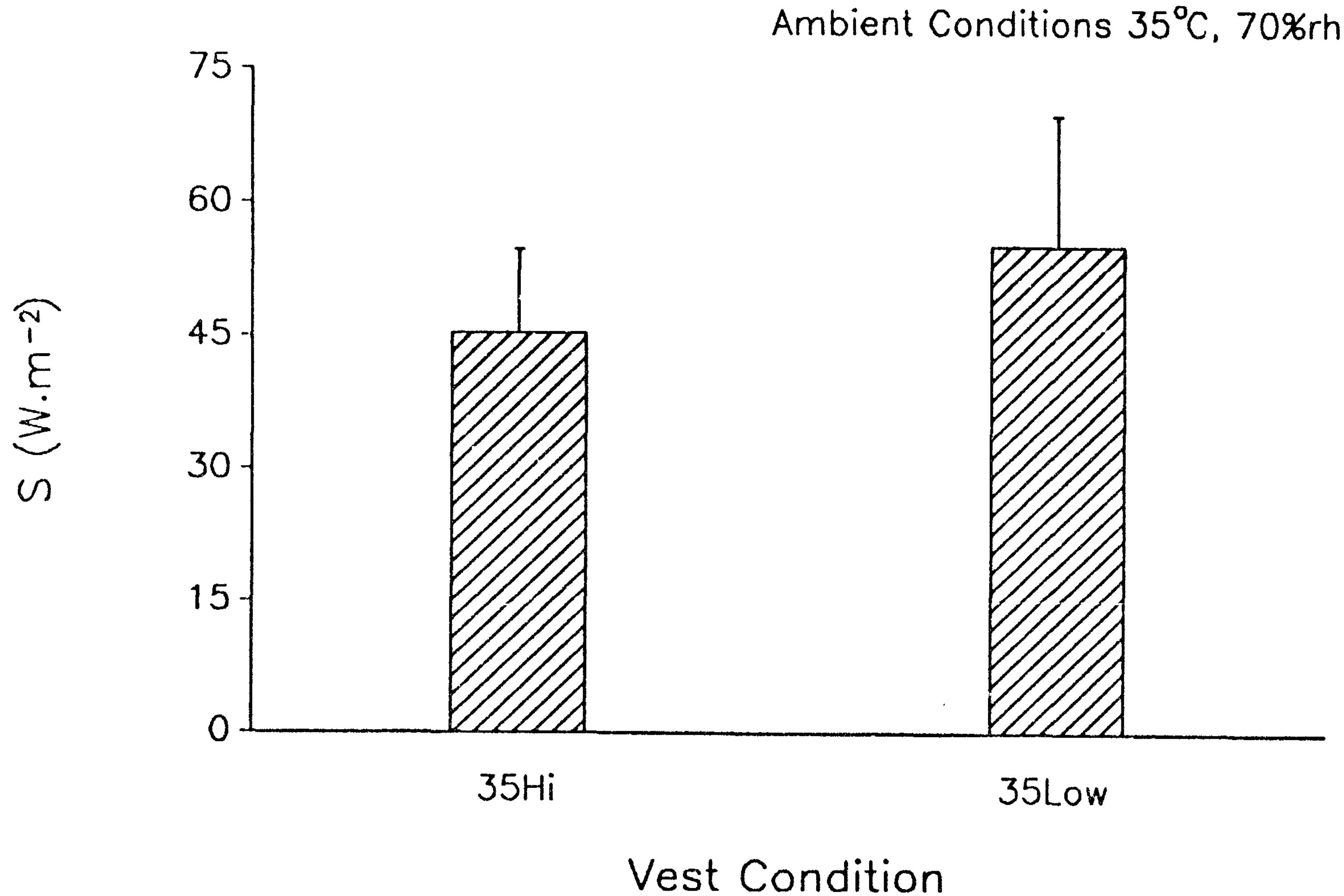

Figure 10 Mean ±SD 36 min heat storage (S) wearing PAV at two flow rates of ambient air.

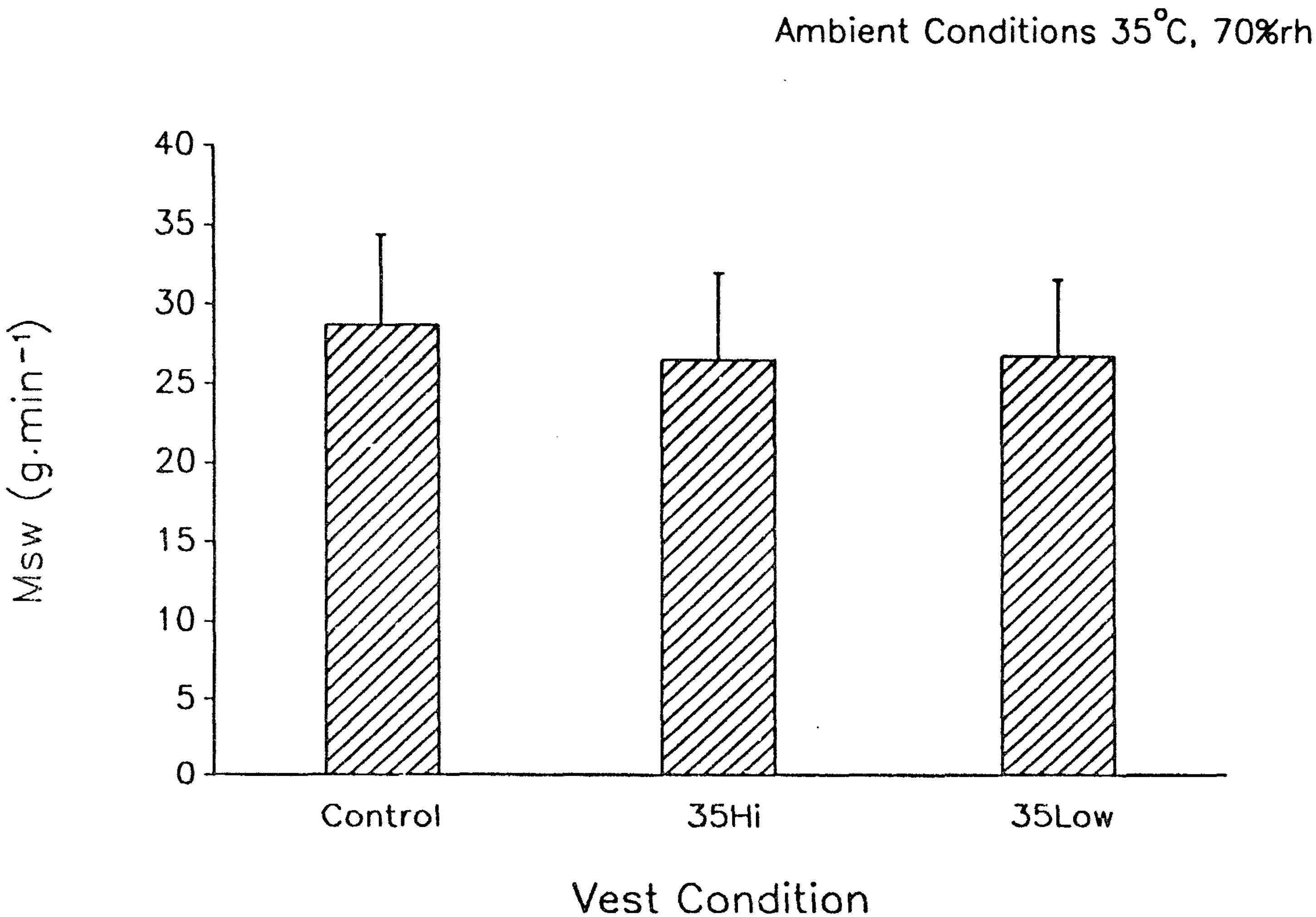

Figure 11 Mean ±SD sweating rates (M_{sw}) wearing the PAV with no cooling (Control) and two flow rates of ambient air.

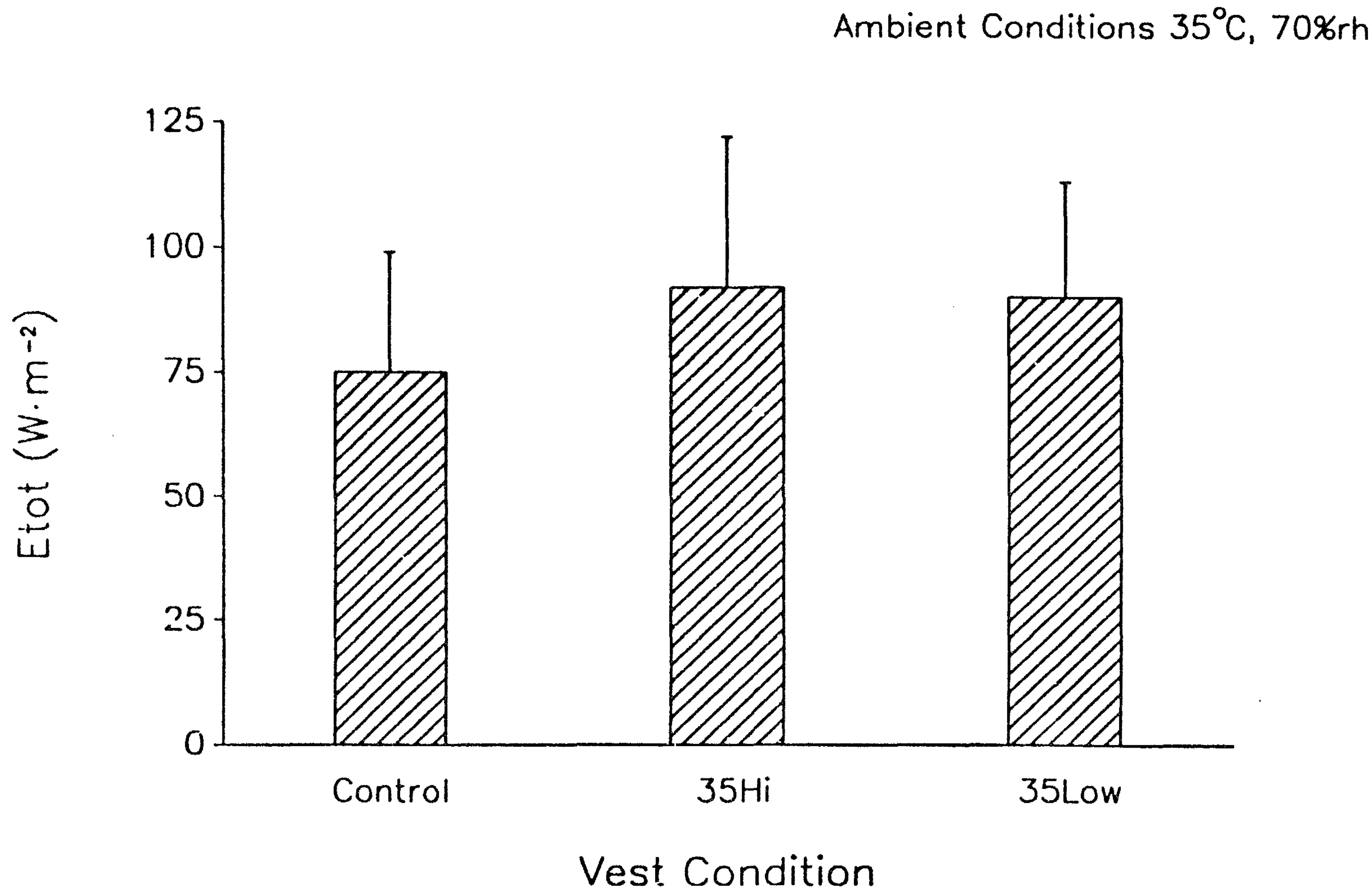

Figure 12 Mean ±SD evaporative cooling (E_{tot}) wearing the PAV with no cooling (Control) and two flow rates of ambient air.

DISCUSSION

This study was designed to examine the effectiveness of the PAV at a work rate and in environments experienced by soldiers in the field. The work rate was chosen to model the typical energy requirements of a soldier involved in prolonged self-paced work (10), and that of a tank crew loader performing his job during a battle scenario (20). This work rate (425 W) was higher than the 200 W and 330 W used to model helicopter pilot and crew members (19), but was chosen because the PAV is being considered as a universal replacement for the MAV. The environmental temperatures were representative of desert and tropic field conditions. The 30°C and 40°C temperatures to the vest were chosen as representative of the range of conditioned temperatures which would reach the loader's vest with the environment at 45°C. The 7.08 $L \cdot sec^{-1}$ flow rate represents air flow as currently provided to the crew of the M1A1, while the 4.72 $L \cdot sec^{-1}$ provided the opportunity to investigate the trade off between temperature and flow rate (ie does 30°C air at Low flow provide more cooling than 40°C air at Hi flow).

The workload used in these experiments resulted in great variability of the subjects ability to tolerate the heat strain, from as little as 28 minutes for one subject receiving cooling at 45Hi to as long as 149 minutes in one subject receiving cooling at 30Hi. This large variability in endurance resulted in the short (28 min) analysis time for data on all subjects in all cooling conditions. One drawback of this short analysis time was no significant difference for core temperatures among any of the cooling configurations. This was due to the slow initial core temperature increase when using rectal values as a marker of thermal strain. Future experiments on the PAV using representative workloads for helicopter pilots and crew members, would likely result in longer exposure times for data analyses. As the use of lower metabolic rates would result in smaller changes in core temperature, the resultant longer exposure times might allow for a more distinct differential among the cooling configurations.

The experiments which directly compared the MAV and PAV clearly showed no difference in any measured physiological response to the exercise heat stress. These experiments indicate that the PAV would be an acceptable replacement for the MAV. The experiments providing 45°C air to the PAV indicate that under some environmental conditions the PAV could be more advantageous than the MAV. The use of ambient air through the PAV at 45°C, 30%rh did not significantly increase the soldiers endurance time over Control. Neither did the 45°C ambient air alter any of the markers of heat stress compared to Control values. However, with the diffuse air flow of the PAV, the volunteers reported no sensation of discomfort or skin burning from the 45°C air passing over their skin. This is a potential advantage over the MAV which resulted in a burning sensation on the skin of subjects during environmental chamber tests with ambient air (49°C) blown through the vest (16). While the PAV was tested at a lower temperature, previous work indicates that skin drying and irritation would occur at 45°C with direct air flow (7). Additionally, while high temperature ambient air to the vest does not by itself increase endurance time, a study by Muza et al. (12) showed an advantage of ambient cooling over no cooling for soldiers exercising in a hot-dry (41°C) environment. These subjects received ambient air during exercise and cooled air during rest periods, leading to decreased heat storage. Ambient air cooling during exercise resulted in lower sweating rates, core temperatures and heart rates during exercise, compared to Control experiments when the subjects received cooling during rest, but ambient air only to the facepiece during exercise. This resulted in an increased exercise endurance of 74 minutes. In the field, this could translate into a benefit from using an ambient blower unit when performing extra vehicular work.

Varying the temperature and flow rates to the PAV, afforded an opportunity to examine the trade off between temperature and flow rate for eliciting optimum performance from the subjects. The 30Hi experiments provided the greatest theoretical cooling (680 W) and resulted in clear cut performance enhancement and the smallest change in measured thermoregulatory responses compared to experiments with no cooling. A comparison between the 40Hi experiments (554 W theoretical cooling) and the 30Low experiments (454 W theoretical cooling) show that while there is no significant difference in performance time between these conditions, the subjects did last significantly longer than Control at 30Low, while they did not at 40Hi. All measured physiological parameters were nearly identical between the 40Hi and 30Low tests, indicating an endurance advantage with lower temperature to the vests if there must be a trade-off between temperature and flow rate.

Unchanged evaporative heat loss among any of the cooling configurations or Control at 45°C demonstrates the compartmentalized effect of the cooling vest. While the torso and face receive dry air-flow for evaporation, most of the body remains isolated from the cooling vest with limited evaporation possible. Therefore, delivery of air flow to the legs and head, increasing the potential for evaporative heat loss, would be beneficial. Providing this air would require modifications to the cooling system, and increased flow rate through the system. Still, even as currently designed, air provided to the system at 30Hi increased endurance time three times longer than Control, indicating that cool air is necessary to increase the soldier's performance time in a high temperature, low humidity environment.

Physiological indicators of thermal strain, e.g. $\bar{T}_{sk}$ and HR, showed the advantage of providing cooling compared to no cooling. Within the cooling configurations provided in the 45°C environment, air at 30°C reduced heat strain (lower $\bar{T}_{sk}$ and HR) compared to blown ambient air. The sweating rate at 30Hi was lower than in Control and 45Low. The reduced heat strain in the 30Hi configuration resulted in less heat storage and greater endurance time compared to Control experiments. These data reconfirm the findings that microclimate cooling increases exercise endurance, prevents dehydration and reduces the water needs of combat troops (11,14). The 35°C_{db}, 28.6°C_{dp} environment provided minimal opportunity for evaporative cooling during exercise with or without MOPP 4. However, blowing ambient air through the cooling system did change both evaporative capacity, and convective cooling capabilities. Providing both high and low flow rates at this ambient temperature over the subjects torso and face increased endurance time 40% compared to no cooling. Also, heat storage was greater during Control than with cooling at both flow rates under these tropic conditions. The high insulative capacity (clo=2.75) of MOPP 4 likely results in a warmer microenvironment inside the uniform of the exercising soldiers than the 35°C dry bulb temperature of the environment. Therefore, blowing 35°C air over the skin provided a small gradient allowing convective cooling directly under the vest. This cooling in combination with positive pressure to the protective mask allowed subjects to increase endurance times compared to Control.

CONCLUSIONS

These experiments were conducted to answer three specific research questions about the effectiveness of a prototype air-cooled vest with design changes that make it useful for helicopter crews as well as armored vehicle crews. The results of these experiments show that: 1) Under matching cooling conditions, the PAV is as effective as the MAV at reducing heat strain and increasing exercise performance time; 2) With the diffuse air-flow provided by the PAV, subjects experience no sensation of contact burning from air delivered at 45°C; 3) In a trade-off between flow rate and inlet temperature, subjects showed improved performance with air provided at 30Low compared to 40Hi even though 40Hi provided greater calculated cooling potential. It is concluded from these results that: 1) The PAV would provide a suitable replacement for the MAV; 2) The PAV could be used at higher ambient temperatures than the MAV; 3) If design changes in vehicle cooling equipment necessitate a trade-off between flow rate and cooling, they should favor providing lower temperatures over higher flow rates.

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